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Approach to an FE simulation of coating damage on bulk metal forming tools

Christian Oppermann *, Gerhard Schmidt, Welf-Guntram Drossel

Fraunhofer IWU, Reichenhainer Straße 88, 09126 Chemnitz, Germany

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ABSTRACT

This paper describes the numerical simulation of failure mechanisms of coated forming tools and explains the procedure of a finite element analysis (FEA) of the coating - substrate - system.
The development of a static failure model is explained using the examples of thermally sprayed and amorphous carbon coatings. Furthermore, its implementation into the FE model is demonstrated. Sprayed thick coatings are used initially, the developed methods are then transferred to amorphous thin coatings. Necessary thermomechanical material properties, especially in the case of thin coatings, as well as system characteristics such as adhesion strength are insufficiently known. Together with FEA several techniques are employed to determine applicable model parameters using parameter identification. The paper only considers monolayers. In a first approximation both substrate and coating are considered homogeneous and isotropic.

1. Fields of application

The field of surface engineering comprehends the selective modification of subsurface material fractions and the addition of secondary materials, i.e. the coating processes, see Fig. 1.

In the present research, the right branch, the coating, is investigated as regards analysis and improvement by the finite element method. As regards the intended application, reduction in friction and adhesion or decrease in abrasive wear, thin and thick coatings have to be distinguished, respectively. The film thickness is process-related and thus serving as a sensible way of distinction as it refers to the coating performances. Both thick and thin coatings have different modes of action, which makes them not convertible. In the following sections, the chosen classification refers to the coating thickness, which is most convenient regarding the future application. In this case, the distinction between thick and thin coatings is based upon the process of coating. Characteristic thicknesses are described below. This classification is not universally valid but rather reasonable in this context. The characterization of the composition, such as monolayers, multilayers or graded layers, is an additional classification, which applies to both coating types. Only monolayers are considered in this investigation. The atomic structure (sp^2/sp^3 bonds) is neglected but is indirectly integrated in the experimentally determined thermomechanical properties. Surface textures are treated as boundary geometry of the FE models.

The considered applications are forming tools that are usually loaded by very high normal stresses, which means high friction stresses. Typical kinds of failure include abrasive wear, cohesive cracking and delamination.

Previous investigations on failure are limited to fatigue strength [1] or crystalline coating materials [2]. Contact stiffness and its influence on the stress distribution, i.e. failure, is investigated [1], especially on cutting tools. Different works analyzing the influence of the geometry of the indentor have been realized [3], and first failure mechanisms have been identified. The importance of the residual stress state has been pointed out for proper strength studies [4]. Dynamic effects have been investigated in association with fatigue strength [5], too.

An important lack of knowledge still exists in the field of statical failure of coatings. The above-mentioned works have been used in this investigation to contribute to this subject. The objective of the realized works is the development of an easy-to-use damage model with easy-to-determine model parameters to be used in the FE simulation. Conventional test methods on coatings such as the scratch test, among others, are not suited for this.

In the following, the coating-substrate system is understood as the whole tool (substrate) together with the coating, whose properties and loads arise from pre-machining, the coating-process and the working conditions of the final tool. A main challenge consists in the very different orders of magnitude of tool geometry in the range of decimeters and of the coating in the submicrometer range. This requires the combination of multiple models with different scales.

* Corresponding author. Tel.: +49 371 5397 1869; fax: +49 371 5397 6 1869.
E-mail address: christian.oppermann@iwu.fraunhofer.de (C. Oppermann).
URL's: http://www.iwu.fraunhofer.de (C. Oppermann),
http://www.iwu.fraunhofer.de (G. Schmidt), http://www.iwu.fraunhofer.de
(W.-G. Drossel).

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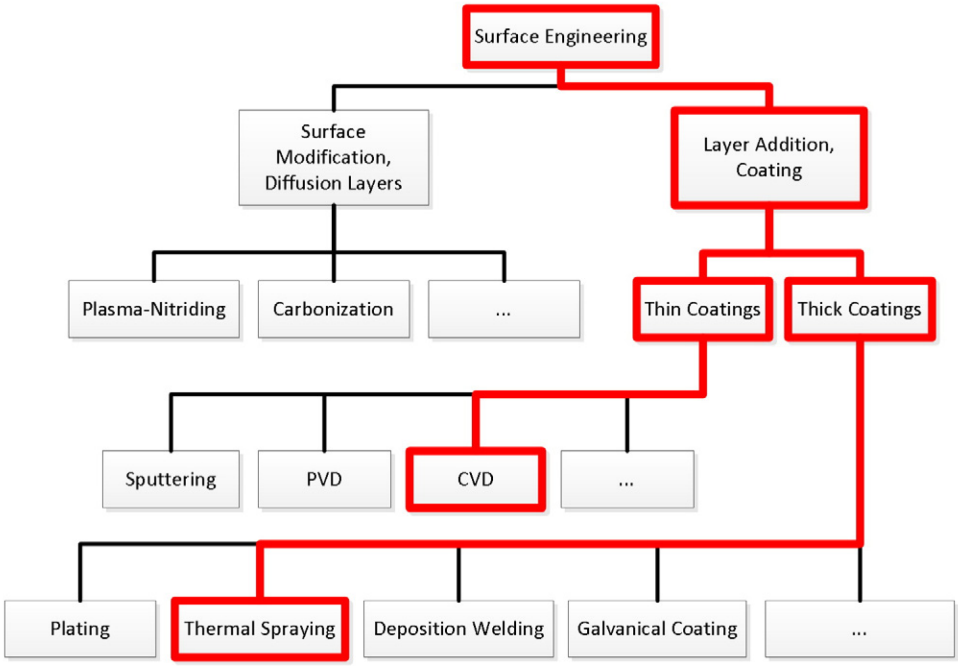

Fig. 1. Surface engineering technologies, highlighted: examined case examples.

1.1. Thick coatings

Thick coatings within the usual range of several tenths of a millimeter do not show extremely low affinity or low friction coefficients nor do they exhibit ultra-high hardness. Their tribological behavior is better than the basic material, and due to their thickness, they do offer a certain wear stock. Additionally, these coatings can have higher corrosive wear resistance if employed under these conditions. Since the coatings are applied using processes of built-up welding or thermal spraying, re-deposition is relatively easy and possible to take place under workshop conditions. It is neither required to use large, closed deposition chambers nor the application under vacuum conditions. Due to this phenomenon, the conventional application of thick coatings is the temporary protection of functional surfaces with the purpose of re-coating. Because of the deposition process, coating surfaces are relatively rough and uneven. Therefore, finishing is often required.

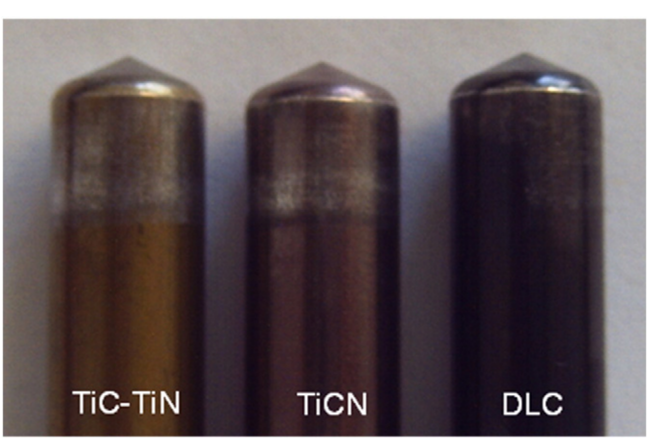

Fig. 2. Coated punches after forming Al 5083 with different grades of adhesive wear (light areas ≙ penetration depth) [6].

1.2. Thin coatings

In contrast, the investigated thin coatings, normally deposited by methods of physical vapor deposition (PVD) or chemical vapor deposition (CVD), show thicknesses in the range of some nanometers up to several micrometers. The overall object is the modification of the tribo-pair by reducing the affinity in case of adhesive wear. Thus, friction is reduced and the shear load on the surface weakens. However, this is mainly a consequence of the lower adhesive affinity. Ultra-hard tetrahedral amorphous carbon coatings (ta-C) reduce wear, they prevent failure due to brittleness of the tool with their ductile substrate. Less hard carbon coatings such as a-C:H-DLC (amorphous-carbon:hydrogen-diamond like carbon) do not have the ultra-high hardness such as ta-C but also take effect in a lower affinity between the contact partners. Other thin coatings like titanium nitride (TiN) or titanium carbide (TiC) have similar functional mechanisms. Fig. 2 shows a comparison of the reduction of adhesive wear of different coatings, using the example of a punch test similar to a forming process. Due to their low thickness, these coatings cannot supply a wear stock with the purpose of re-coating worn surfaces. These layers map the topology of the substrate surface; finishing is not necessary. In case of rough substrate surfaces, however, pre-machining might be needed.

Table 1
Required mechanical and thermal material parameters.

Parameter	Abbreviation	Dimension
Young's modulus	E	$\frac{N}{mm^2}$
Poisson's ratio	ν	–
Yield stress	σ_Y	$\frac{N}{mm^2}$
Ultimate tensile stress	UTS	$\frac{N}{mm^2}$
Braking strain	A	–
Coefficient of thermal expansion	CTE	$\frac{1}{K}$
Heat conductivity	λ	$\frac{W}{m \cdot K}$
Specific heat	c_p	$\frac{J}{kg}$
Density	ρ	$\frac{kg}{m^3}$
Heat transmission coefficient	h	$\frac{W}{m^2 \cdot K}$